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EVALUATION OF THE PROTECTIVE EFFICIENCY OF A NEW
OXYGEN MASK FOR AIRCRAFT PASSENGER USE TO 40,000 FEET

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16. Abstract This report describes the methods used in the evaluation of a new continuous-flow, phase-dilution passenger oxygen mask for compliance to FAA Technical Standard Order (TSO)-C64 requirements. Data presented include end expiratory partial pressures for oxygen, carbon dioxide, and nitrogen at selected altitudes and oxygen flow rates. Data indicate that the test mask does meet the requirements for TSO-C64 certification. A			
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EVALUATION OF THE PROTECTIVE EFFICIENCY OF A NEW
OXYGEN MASK FOR AIRCRAFT PASSENGER USE TO 40,000 FEET

INTRODUCTION

Various types of oxygen masks have been carried aboard transport category aircraft to provide breathing oxygen for passengers and flight attendants in the event of a loss of cabin pressurization. Most passenger oxygen masks in current use are of the continuous-flow, phase-dilution type that are very economical in the amount of oxygen required for proper functioning, yet provide sufficient oxygen to the passenger to maintain useful consciousness. In the event of a decompression, most aircraft oxygen systems are designed to automatically present the mask to the passenger and, if oxygen flow is properly activated, regulate the amount of oxygen delivered to the mask as a function of cabin pressure. If chemical generator systems are used as the source of oxygen, flow control is accomplished by a geometrically shaped active core which is designed to produce oxygen at predetermined rates.

Mask performance and testing criteria are specified in Technical Standard Order (TSO)-C64, Oxygen mask assembly, continuous flow, passenger (for air carrier aircraft) (1); and in National Aerospace Standard (NAS)-1179, Oxygen Mask Assembly, Passenger (2). These specifications require that an adequate oxygen flow curve, accounting for mask leakage, be established for the altitude range within which the mask is to be used. Oxygen flow rates from the established curve are then used in the ultimate performance test specified in NAS-1179 (paragraph 4.1.8) which requires that 10 human subjects be tested in an altitude chamber to the maximum altitude for which the mask is to be certified. Minimum end expiratory oxygen and maximum nitrogen partial pressures are specified for each test altitude or, if ear oximetry is used, minimum blood oxygen saturation values are specified. NAS-1179 further requires that 3 of the 10 subjects must, within 5,000 ft* of the maximum certified altitude for the mask, achieve a respiratory minute volume of nearly 30 L/min body temperature and pressure, saturated (BTPS).

The methods used and data presented in this report are those resulting from an evaluation of a new continuous-flow passenger oxygen mask (Puritan-Bennett Aero Systems Company No. 174080) in compliance with the requirements of NAS-1179 for altitude chamber testing with human subjects in support of TSO-C64 certification.

METHODS

A respiratory mass spectrometer (Perkin-Elmer MGA-1100) that provided on-line analyses for oxygen, nitrogen, and carbon dioxide of each breath was used as the primary analytical instrument. A sample volume totaling 15 mL each minute was continuously drawn from the mask for gas analysis.

*5000 ft (1524m). In order to be consistent with the units commonly used in the aircraft industry, in aircraft instrument displays, and in air traffic control flight levels, all altitudes in this report will be expressed in feet.

Digital readouts for carbon dioxide, nitrogen, and oxygen provided instantaneous monitoring of mask performance. A Honeywell Model 1858 fiber-optic oscillograph was used to produce high-speed analog recordings of the gas analyses from the mass spectrometer. The mass spectrometer was equipped with four capillary inlets and selector switches, which allowed the capillary diameter to be matched to chamber pressure and gas density (Figure 1). The capillaries were connected to a common manifold system that was supported by a head strap worn by the subject. The manifold was then connected to the mask cavity by a short piece of PE-60 tubing. This proved to be a satisfactory method for preventing capillary weight and/or movement from affecting mask performance during testing. The mass spectrometer was calibrated in the static mode through the continuous sampling of calibration grade gas mixtures and in the dynamic mode by alternating gases every 3 to 5 seconds with a multiple selector gas chromatography valve (Figure 2). A Med-Science Electronics Nitralizer, used as a secondary analytical system, provided an independent backup analysis of mask nitrogen levels. A second Nitralizer was used to monitor chamber environment to insure that the oxygen content within the chamber did not increase significantly (Figure 1).

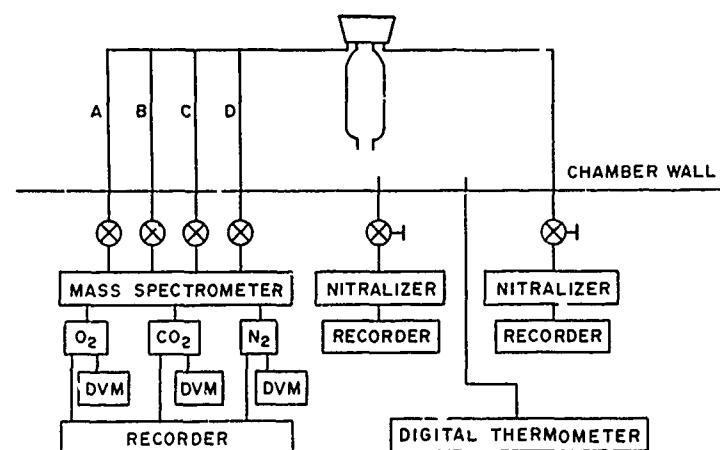


Figure 1. Analytical diagram for mask testing in altitude chamber. A-capillary for 0 to 11,000 ft; B-capillary for 11,000 to 21,000 ft; C-capillary for 21,000 to 31,000 ft; D-capillary for 31,000 to 41,000 ft.

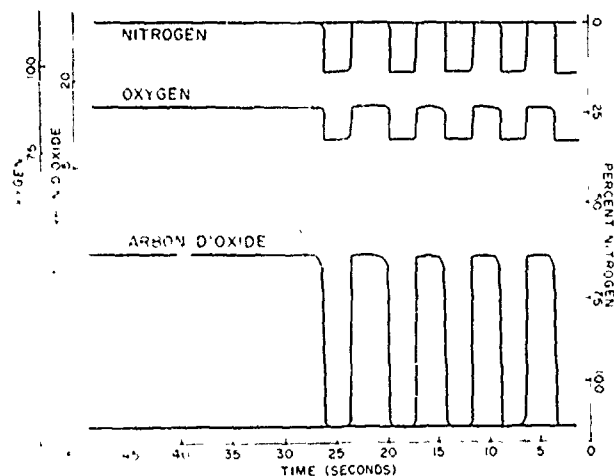


Figure 2. Typical static and dynamic calibration recording from the mass spectrometer.

Oxygen delivery to the test mask was regulated by a flow-control module that contained five parallel flow circuits, each consisting of an on-off pneumatic valve and an adjustable flow orifice. Each circuit was set to deliver the prescribed flow to the mask for a given altitude (Table 1). Each circuit was calibrated at ground level with a National Instruments Laboratory liquid flowmeter and simultaneously recorded with a Celesco electronic transducer coupled to a Hewlett-Packard recorder (Figure 3). The liquid flowmeter was then removed from the system and calibrations at altitude were verified with the electronic transducer. During testing, the recording system provided rapid verification of proper oxygen flow to the mask for each respective altitude. The flow control module also contained a purge circuit that provided 10 L/min normal temperature and pressure, dry (NTPD) oxygen flow to the mask, an emergency cutoff switch (for fire safety purposes), and a pressure regulating and monitoring system.

An aircraft crewmember seat, track mounted in line with a Quinton bicycle ergometer, allowed the subject to be seated during testing. The ergometer controls were located outside the chamber where a constant work mode could be set to obtain the desired increase in the subject's ventilation rate. When exercising, the subject wore a crewmember quick-don type oxygen mask with large bore delivery hose coupled to a gas flowmeter which allowed the ventilation rate to be measured in relation to exercise levels. During nitrogen washout at 14,000 ft (Figure 4-C), the subject wore a crewmember quick-don type oxygen mask with a mask-mounted regulator set to deliver 100 percent oxygen with emergency pressure.

TABLE 1. Oxygen Flow to Mask and Maximum Partial Pressure of Nitrogen Allowed in the Mask at Test Altitudes

Altitude (ft)	Flow (L/min-NTPD)	mmpN ₂ (mm Hg)
14,000	0.34	300
21,500	1.27	197
29,000	2.13	100
35,000	2.68	48
40,000	3.10	10

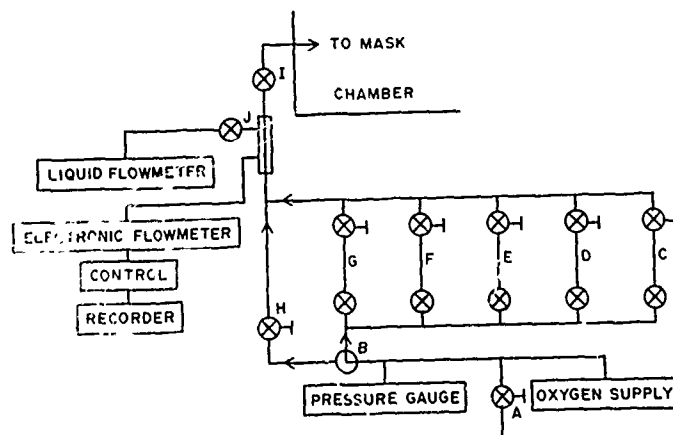


Figure 3. Diagram for oxygen flow control system.
A-variable orifice for regulating pressure; B-selector valve; C-flow control for 14,000 ft; D-flow control for 21,500 ft; E-flow control for 29,000 ft; F-flow control for 35,000 ft; G-flow control for 40,000 ft; H-purge valve; I-emergency cutoff valve; J-cutoff valve.

A three-lead electrocardiogram was used to monitor heart activity and rate. A 16-mm motion picture camera and associated lighting were positioned to record the subject's face, the test mask, a timer, and a digital altimeter. A platinum resistance thermometer was used to monitor chamber temperature. Data reduction was accomplished using a Hewlett-Packard Model 9820 computer equipped with digitizer and X-Y plotter accessories. Calibration gases were Matheson Primary Standard grade mixtures and oxygen was Aviator's Breathing Oxygen.

TEST PROCEDURES

Selected facial and head measurements were obtained from each subject and compared to U.S. Air Force data (3). Each subject was briefed regarding the purpose of the study, the chamber profile, mask design and function, exercise procedures (if appropriate), analytical methods, potential hazards, and emergency procedures should such become necessary. Electrocardiogram leads were then attached to the subject and a baseline tracing was recorded. Oxygen masks were adjusted to fit the facial contours of the subject, and the continuity of the sampling capillaries was checked.

After checking the capability of the subject and inside observer to equalize ear pressures (Figure 4-A), the chamber was decompressed to 14,000 ft at a rate of 6,000 ft/min. If exercise was included in the test sequence, the subject donned the appropriate mask and began to exercise (Figure 4-B). The resistance to the bicycle ergometer was adjusted until a ventilation rate of approximately 30 L/min was achieved. The subject then stopped exercising, changed crew masks, adjusted the mask-mounted regulator to obtain 100 percent oxygen with emergency pressure, and began a 15-minute nitrogen washout period (Figure 4-C). The chamber was then decompressed to 30,000 ft and the subject donned the test mask (Figure 4-D). The inside observer assisted the subject in changing masks and completed capillary connections to the mask. The chamber was then decompressed to 40,000 ft and the oxygen flow to the mask was adjusted by switching to the corresponding circuit in the flow-control module. Sufficient time was allowed for stable conditions to develop, after which a 3-minute data recording was obtained. The remaining test profile as presented in Figure 4 was completed.

RESULTS AND DISCUSSION

Subject Selection: The subjects' ages ranged from 22 to 62 years. The subjects were selected to minimize the possible development of dysbarism by avoiding excessively obese individuals. Head and facial dimensions for 8 of the 10 subjects fell within the 5th to 95th percentile ranges as established by the U.S. Air Force Anthropometric Survey, 1967 (3). Two of the subjects were deliberately selected to be near or beyond the 5th to 95th percentile 1967 Air Force data for face length (120.3 ± 6.1 mm) and head breadth (156.0 ± 5.4 mm). Subject 216 had a very long, narrow face (face length - 135mm, head breadth - 146mm) and subject 217 had a short, narrow face (face length - 110mm, head breadth - 147mm).

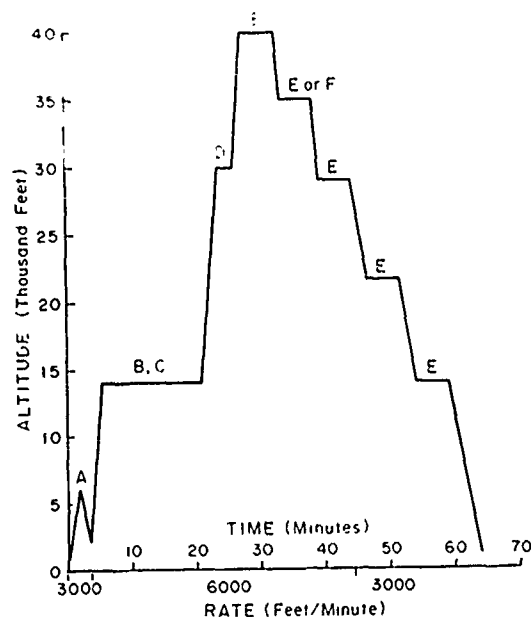


Figure 4. Altitude chamber profile used in mask testing.
 A-earcheck; B-exercise, if appropriate; C-nitrogen washout;
 D-changed to test mask; E-recording without exercise;
 F-recording with exercise.

Respiratory Rate: Respiratory rates, in number of breaths per minute, for each subject at each test altitude and mask oxygen flow in liters per minute (NTPD) are presented in Figures 5 through 14 and are summarized in Table 2. Subject 212 was the only one who showed obvious apprehension on decompressing to 40,000 ft. This subject had a respiratory rate of 23/min at 40,000 ft which decreased to 10/min at 14,000 ft (Figure 9). Film analyses for depth of respiration verified a pronounced hyperventilation at 40,000 ft; however, other visually detectable symptoms that could be caused by hyperventilation were not present. Figures 7, 11, and 13 contain data derived from the three subjects who exercised at 35,000 ft. Respiratory rates, in combination with film analyses for depth of respiration, indicate that the desired increase in ventilation rate was achieved through exercise.

TABLE 2. Summary of Respiratory Data for All Subjects and Test Conditions

Altitude (ft)	Exercise	Minute	Number of Subjects	Breaths/min	
				Mean	Standard Deviation
14,000	0	1	10	11	3
	0	2	10	11	3
	0	3	10	11	3
21,500	0	1	10	12	4
	0	2	10	11	5
	0	3	10	12	4
29,000	0	1	10	12	3
	0	2	10	12	3
	0	3	10	12	3
35,000	0	1	7	12	3
	0	2	7	13	3
	0	3	7	14	3
	+	1	3	14	2
	+	2	3	16	2
	+	3	3	16	3
40,000	0	1	10	13	5
	0	2	10	13	4
	0	3	10	12	5

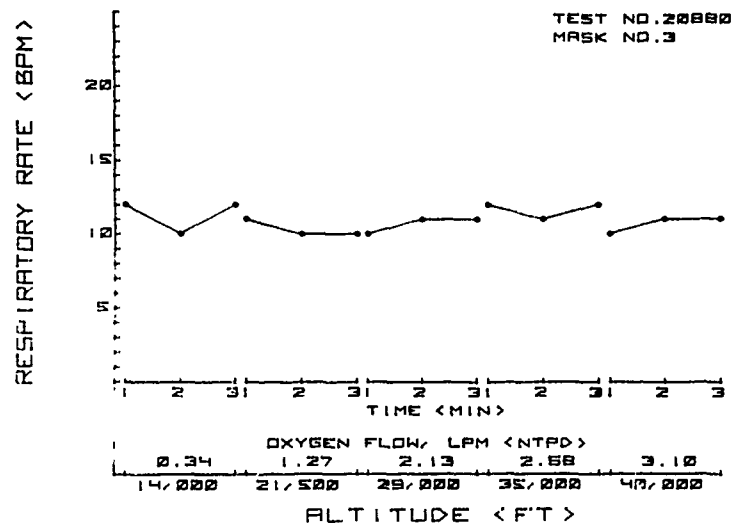


Figure 5. Respiratory rate in breaths/min at each altitude and oxygen flow.
Subject No. 208.

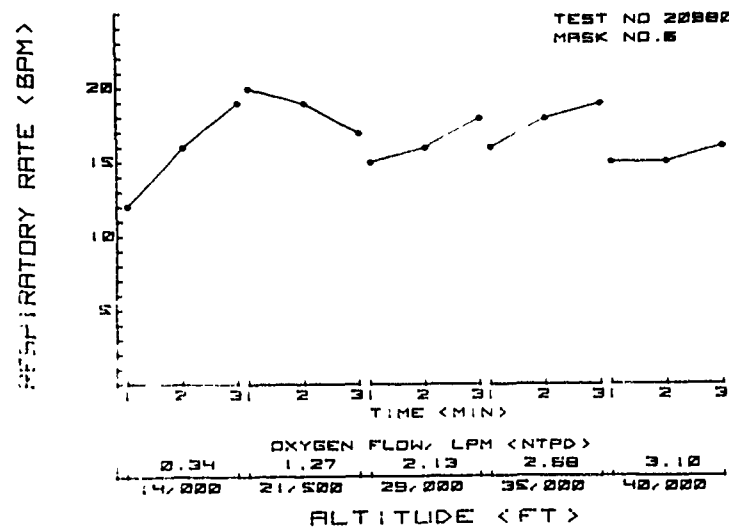


Figure 6. Respiratory rate in breaths/min at each altitude and oxygen flow.
Subject No. 209.

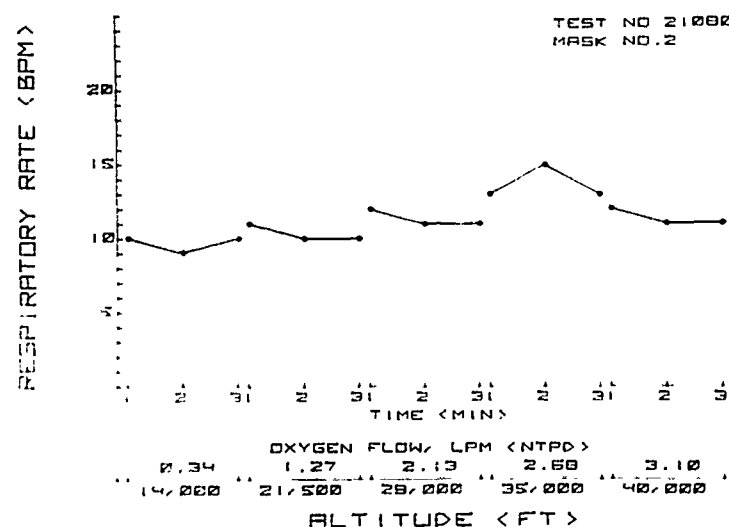


Figure 7. Respiratory rate in breaths/min at each altitude and oxygen flow.
Subject No. 210.

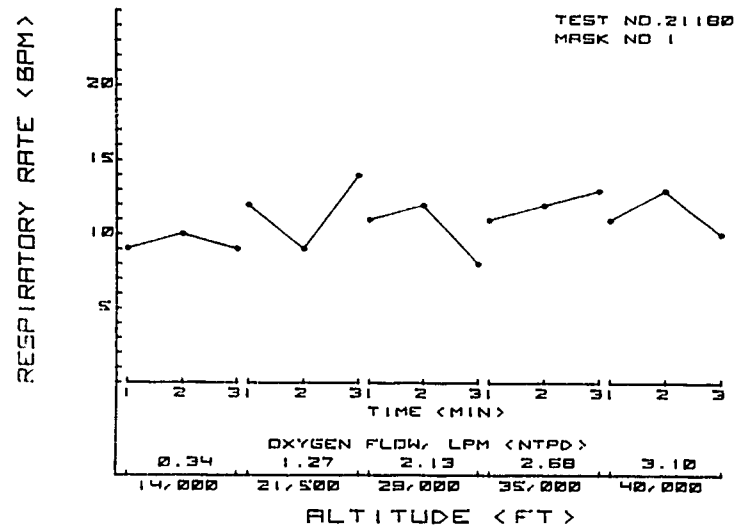


Figure 8. Respiratory rate in breaths/min at each altitude and oxygen flow.
Subject No. 211.

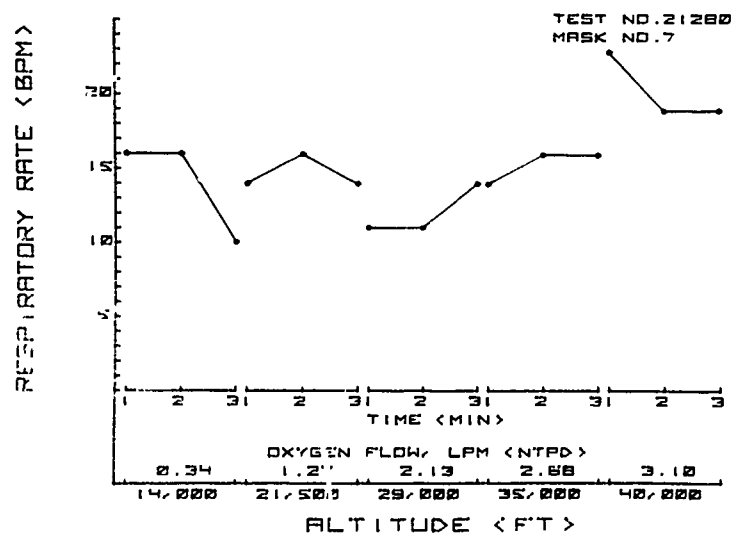


Figure 9. Respiratory rate in breaths/min at each altitude and oxygen flow.
Subject No. 212.

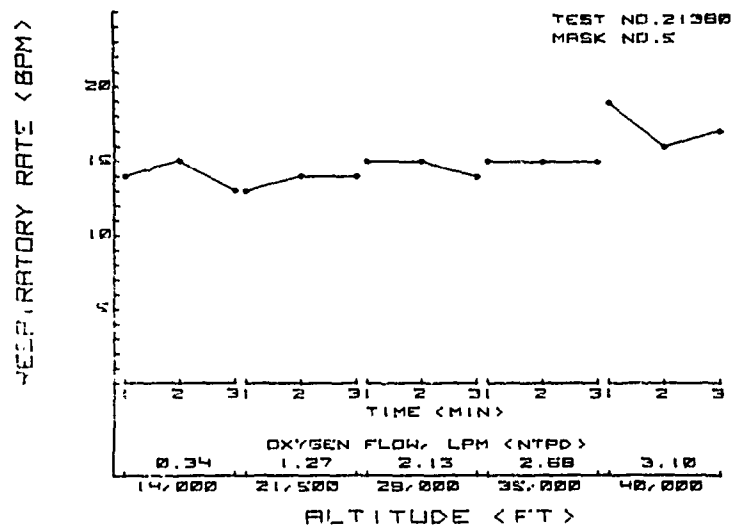


Figure 10. Respiratory rate in breaths/min at each altitude and oxygen flow.
Subject No. 213.

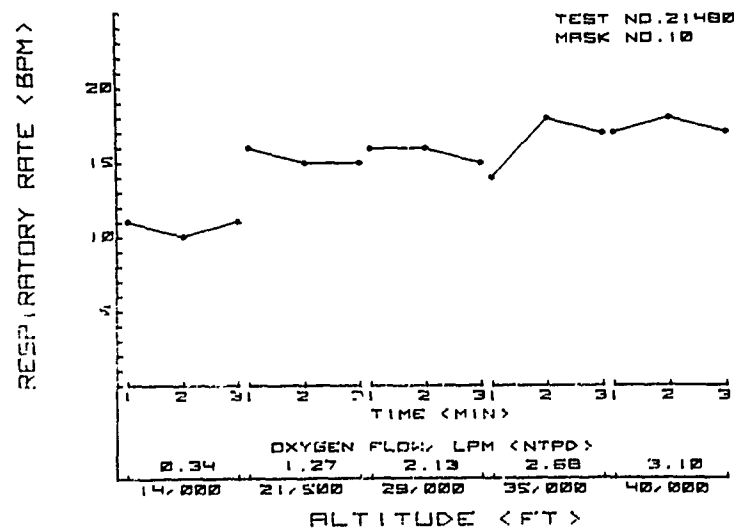


Figure 11. Respiratory rate in breaths/min at each altitude and oxygen flow.
Subject No. 214.

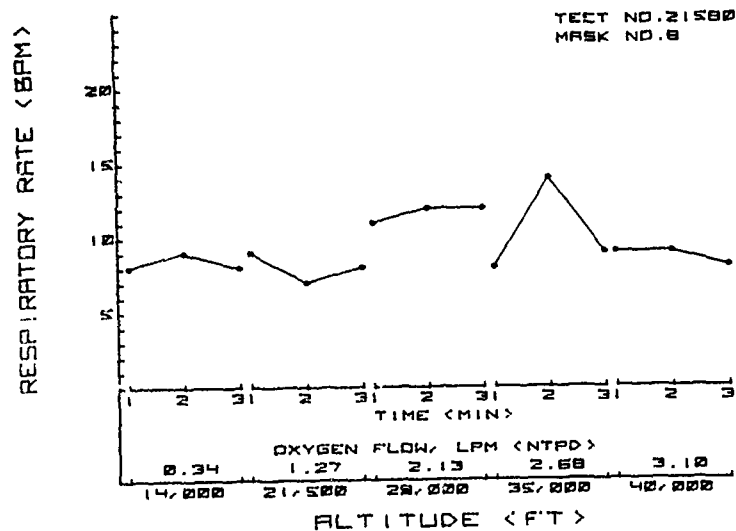


Figure 12. Respiratory rate in breaths/min at each altitude and oxygen flow.
Subject No. 215.

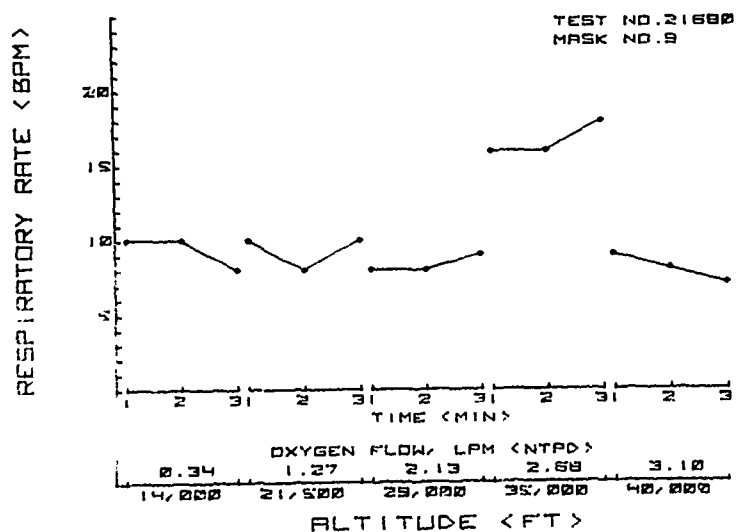


Figure 13. Respiratory rate in breaths/min at each altitude and oxygen flow.
Subject No. 216.

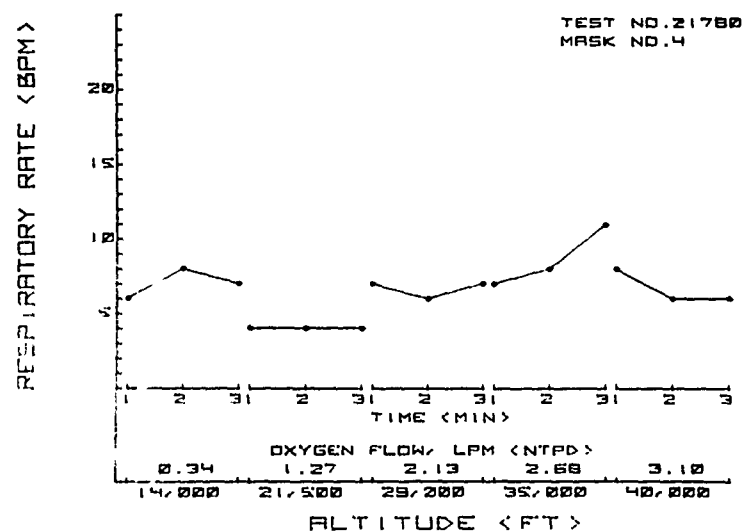


Figure 14. Respiratory rate in breaths/min at each altitude and oxygen flow.
Subject No. 217.

Mask Efficiency: The results obtained from end expiratory gas analyses by mass spectrometry techniques are presented in Figures 15 through 24 for oxygen, Figures 25 through 34 for carbon dioxide, and Figures 35 through 44 for nitrogen. Means and standard deviations for end expiratory gases are presented for 3-minute increments at each altitude and oxygen flow tested.

Excessive nitrogen (>10.3 mmHgN₂) was present in the end expiratory gas for subject 216 (a long, thin face) at 40,000 ft (Figure 43). The mask was visibly separated from his face along one side, allowing inboard leakage. The subject's respiratory and ventilation rates remained low, and he did not indicate or exhibit symptoms of hypoxia. Upon completion of the 40,000-ft test period, the subject yawned, whereupon the mask properly positioned on his face and nitrogen levels decreased to an acceptable level. As there were no further problems, even when the subject exercised at 35,000 ft, it was unnecessary to restructure the oxygen flow curve.

End expiratory nitrogen levels in all other tests were below the maximum limits, even when hyperventilation occurred. Increasing nitrogen levels from 40,000 to 14,000 ft reflect the increasing total pressure and decreasing oxygen flow to the mask. Oxygen flow, while sufficient, was most critical at 14,000 ft (Table 1) with subjects 209 and 216 (Figures 36 and 43) approaching the maximum allowable nitrogen (300 mmHgN₂) for that

altitude. All other values for nitrogen were considerably below the allowable levels for the respective altitudes: an indication of proper mask function, a good mask to face fit, and a sufficient oxygen flow curve.

The data for end expiratory oxygen is in agreement with the corresponding nitrogen data. Increasing oxygen levels from 40,000 to 21,500 ft reflect the increasing total pressure and a flow curve in excess of the minimum necessary to maintain proper mask levels. End expiratory oxygen levels decreased at 14,000 ft due to the sharply decreased flow to the mask at that altitude (Table 1).

End expiratory carbon dioxide gradually decreased as altitude increased to 29,000 ft, then decreased more rapidly as altitude increased to 40,000 ft. Hyperventilation would normally be suspected as the cause for these decreases; however, the data do not support this conclusion. A more likely explanation for the low pCO_2 values is a combination of a low respiratory minute volume and the high expansion ratio (BTPS/NTPD of approximately 8.5 at 40,000 ft) for oxygen delivered to the mask. With this combination, once the reservoir bag has fully expanded, the oxygen inlet valve in the mask would crack open due to a slight pressure differential. This condition allows a continuous flow of oxygen through the mask, resulting in a dilution of the carbon dioxide. Analyses of film data for reservoir bag distension support this conclusion.

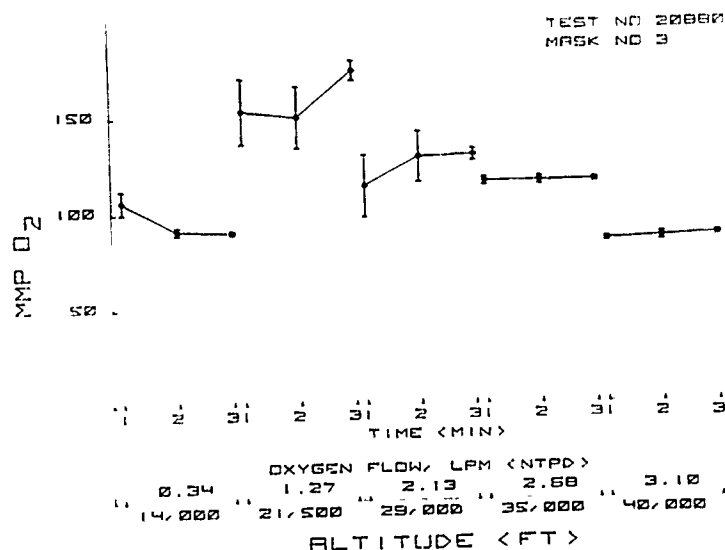


Figure 15. Partial pressure of end expiratory oxygen in mmHg at each altitude and oxygen flow. Subject No. 208.

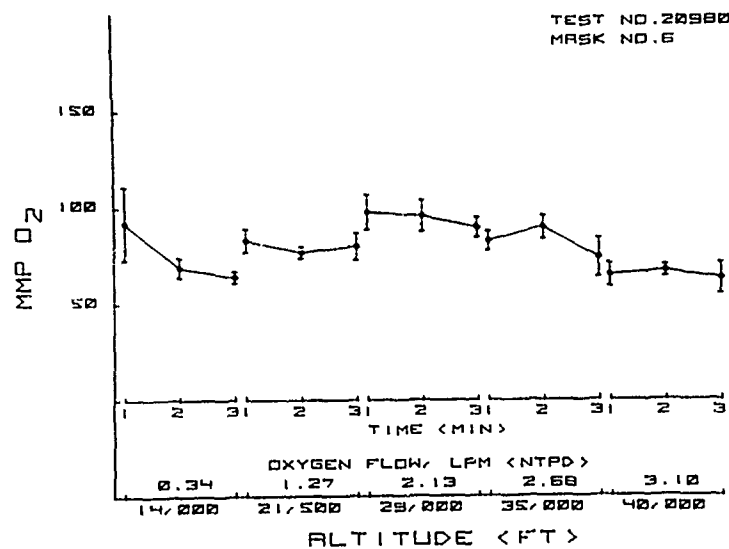


Figure 16. Partial pressure of end expiratory oxygen in mmHg at each altitude and oxygen flow. Subject No. 209.

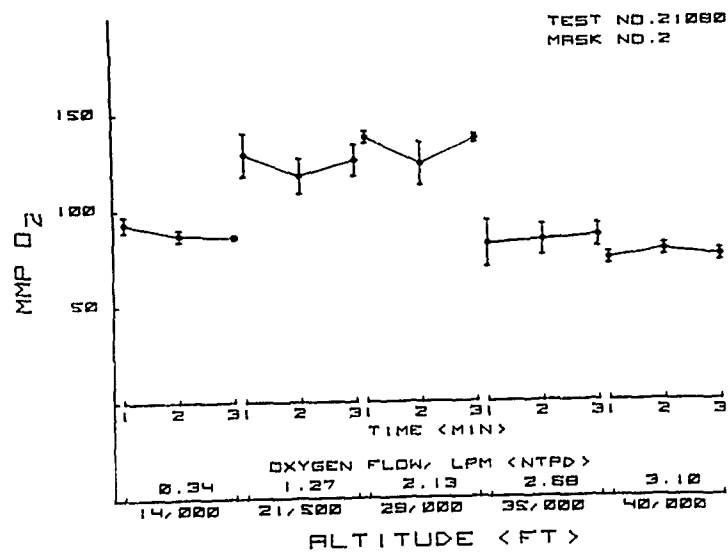


Figure 17. Partial pressure of end expiratory oxygen in mmHg at each altitude and oxygen flow. Subject No. 210.

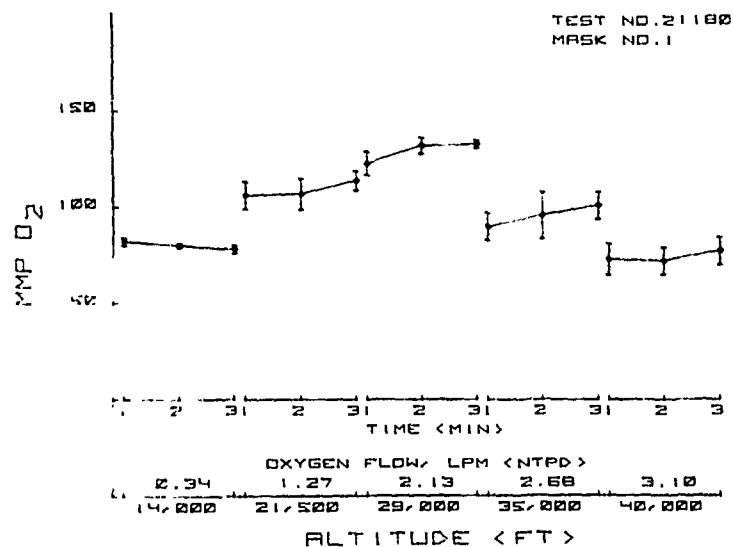


Figure 18. Partial pressure of end expiratory oxygen in mmHg at each altitude and oxygen flow. Subject No. 211.

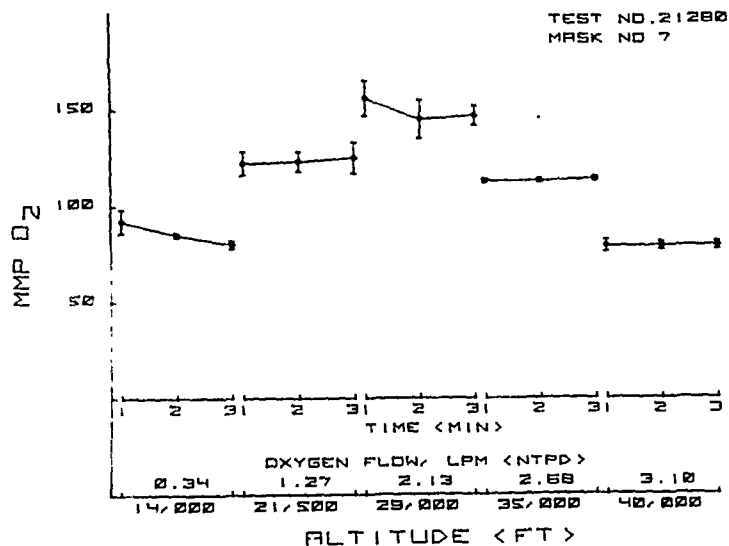


Figure 19. Partial pressure of end expiratory oxygen in mmHg at each altitude and oxygen flow. Subject No. 212.

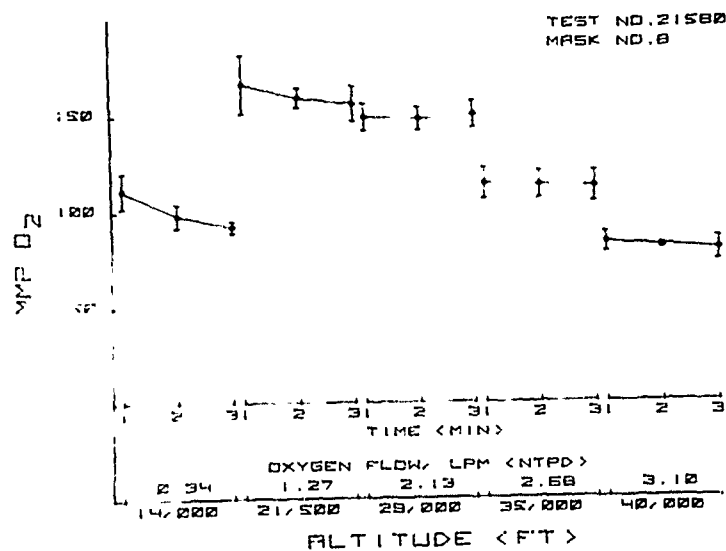


Figure 22. Partial pressure of end expiratory oxygen in mmHg at each altitude and oxygen flow. Subject No. 215.

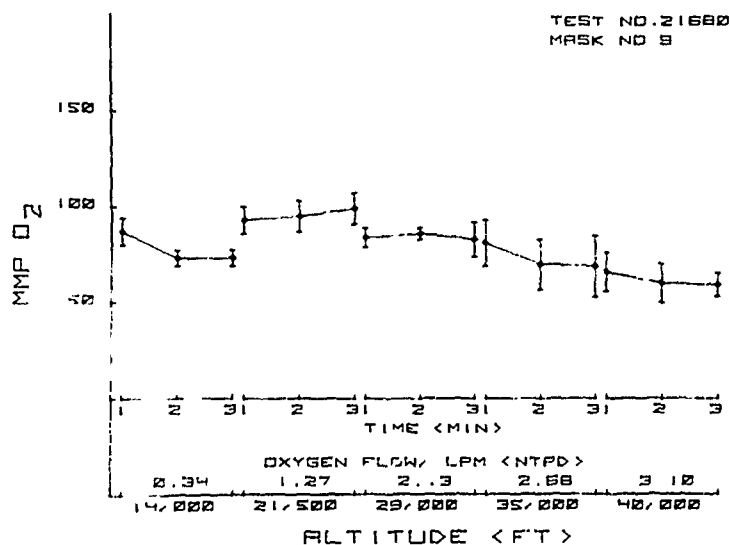


Figure 23. Partial pressure of end expiratory oxygen in mmHg at each altitude and oxygen flow. Subject No. 216.

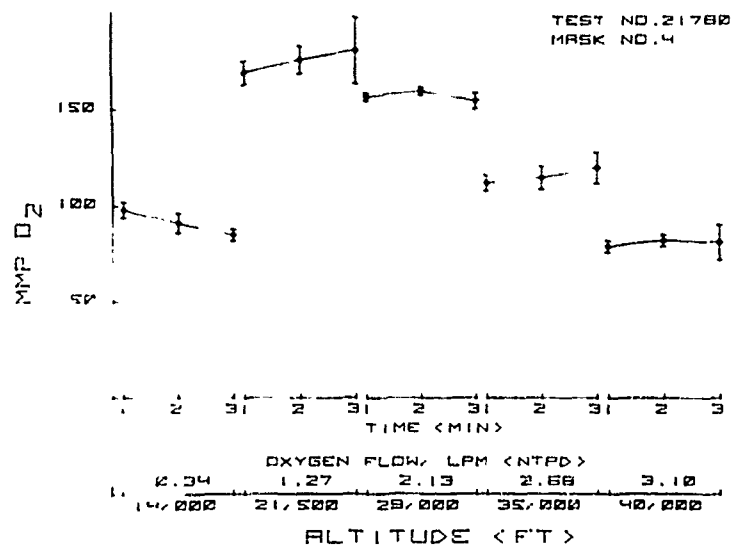


Figure 24. Partial pressure of end expiratory oxygen in mmHg at each altitude and oxygen flow. Subject No. 217.

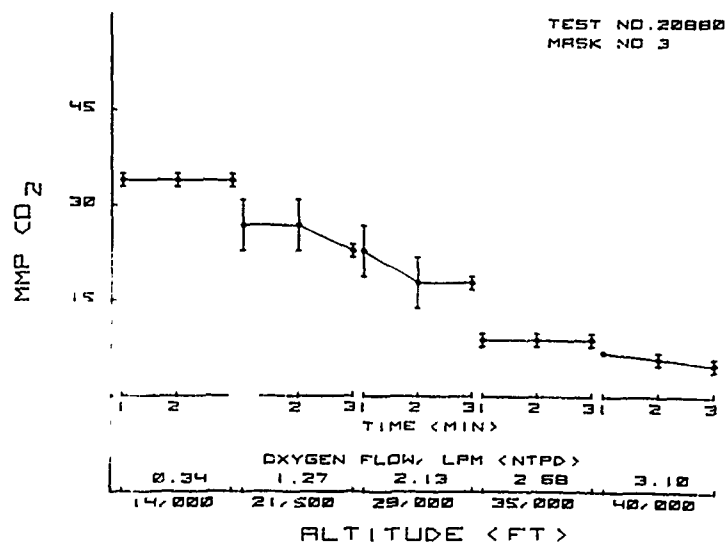


Figure 25. Partial pressure of end expiratory carbon dioxide in mmHg at each altitude and oxygen flow. Subject No. 208.

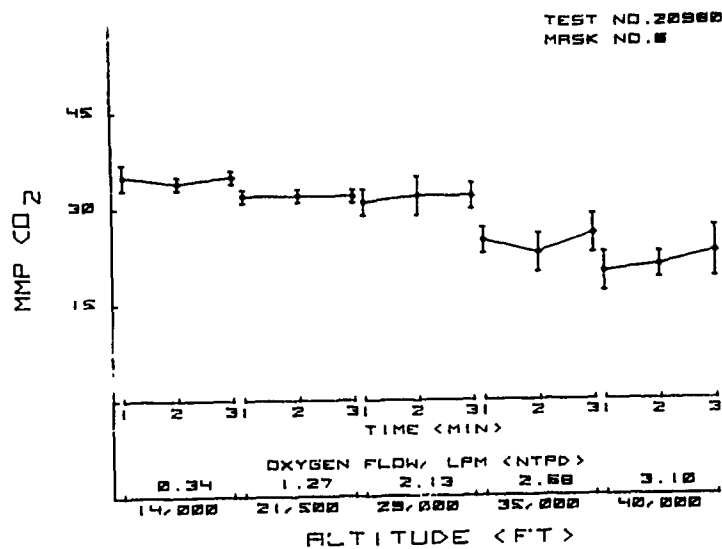


Figure 26. Partial pressure of end expiratory carbon dioxide in mmHg at each altitude and oxygen flow.
Subject No. 209.

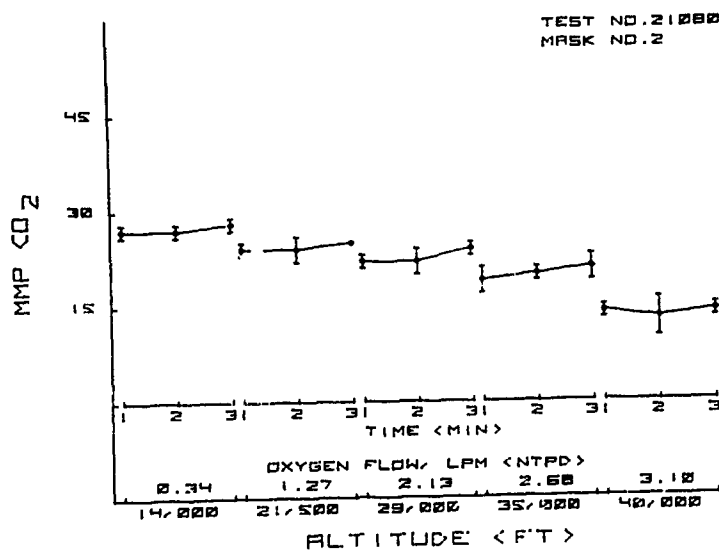


Figure 27. Partial pressure of end expiratory carbon dioxide in mmHg at each altitude and oxygen flow.
Subject No. 210.

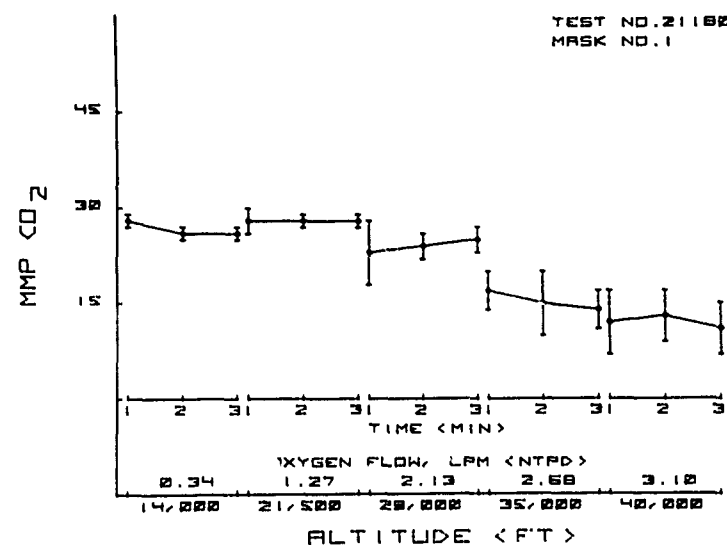


Figure 28. Partial pressure of end expiratory carbon dioxide in mmHg at each altitude and oxygen flow. Subject No. 211.

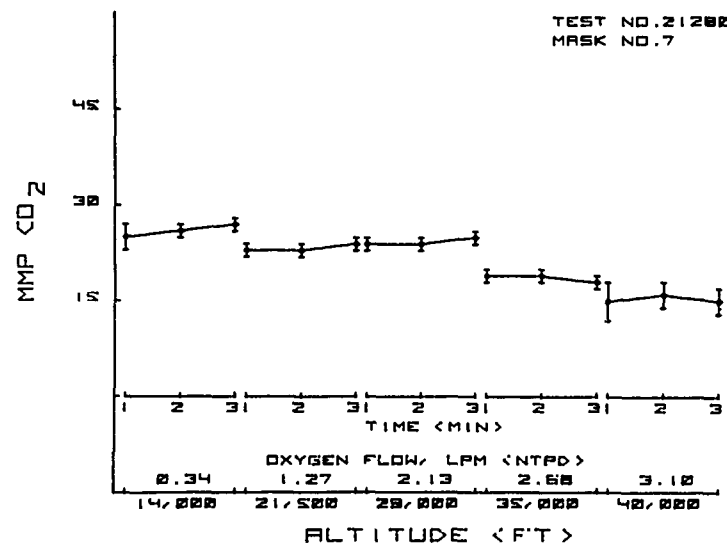


Figure 29. Partial pressure of end expiratory carbon dioxide in mmHg at each altitude and oxygen flow. Subject No. 212.

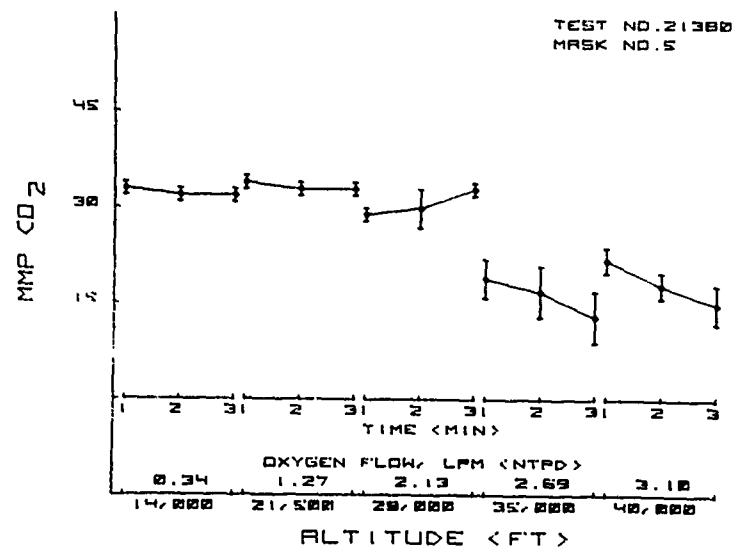


Figure 30. Partial pressure of end expiratory carbon dioxide in mmHg at each altitude and oxygen flow. Subject No. 213.

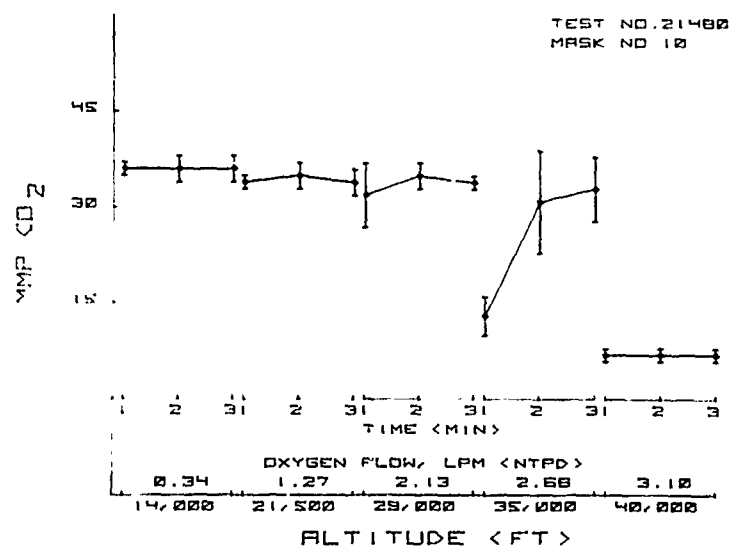


Figure 31. Partial pressure of end expiratory carbon dioxide in mmHg at each altitude and oxygen flow. Subject No. 214.

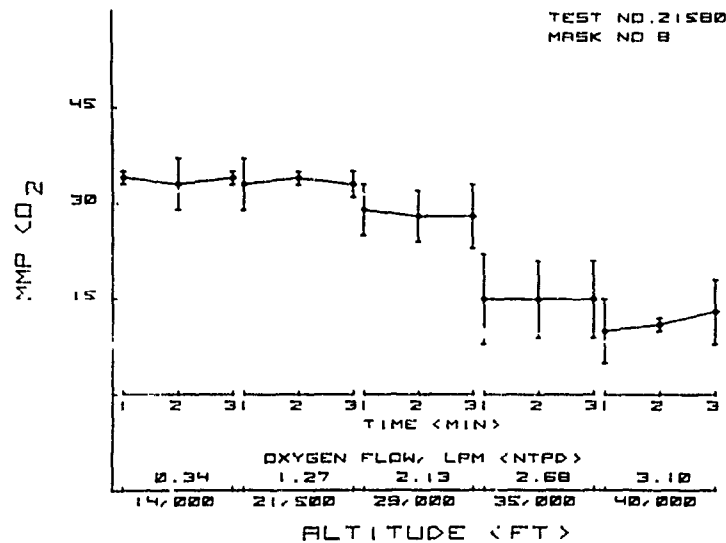


Figure 32. Partial pressure of end expiratory carbon dioxide in mmHg at each altitude and oxygen flow. Subject No. 215.

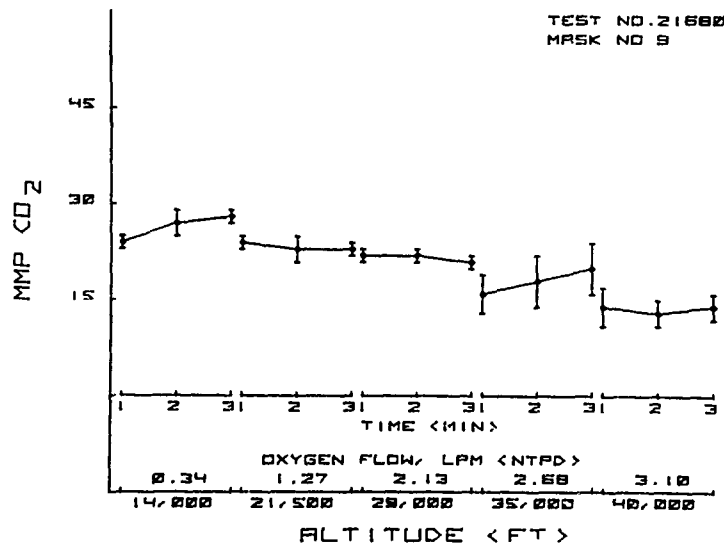


Figure 33. Partial pressure of end expiratory carbon dioxide in mmHg at each altitude and oxygen flow. Subject No. 216.

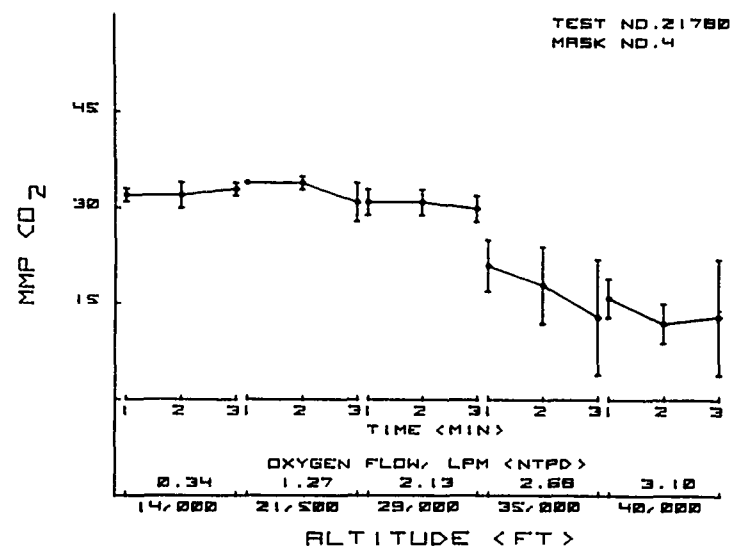


Figure 34. Partial pressure of end expiratory carbon dioxide in mmHg at each altitude and oxygen flow. Subject No. 217.

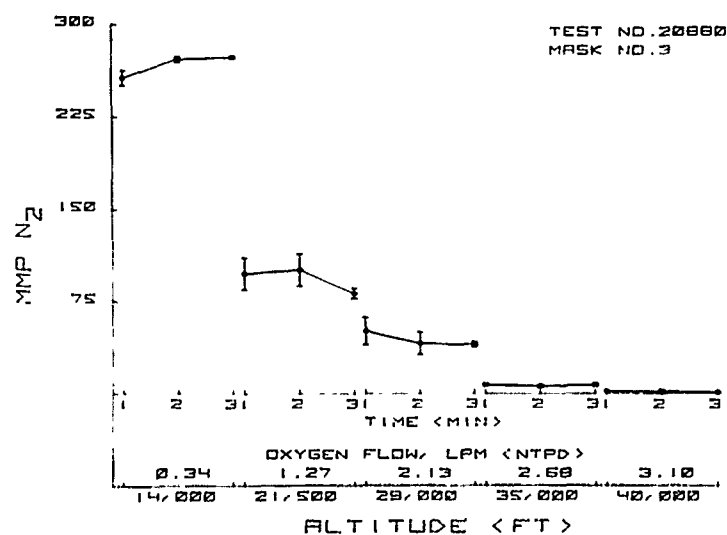


Figure 35. Partial pressure of end expiratory nitrogen in mmHg at each altitude and oxygen flow. Subject No. 208.

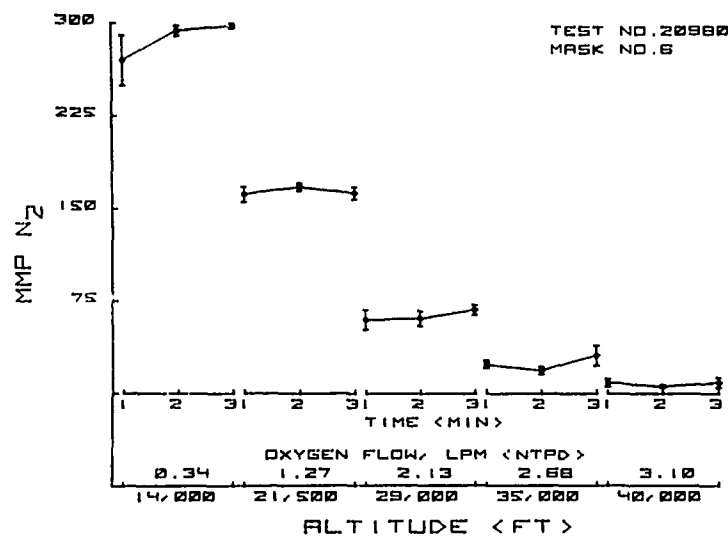


Figure 36. Partial pressure of end expiratory nitrogen in mmHg at each altitude and oxygen flow. Subject No. 209.

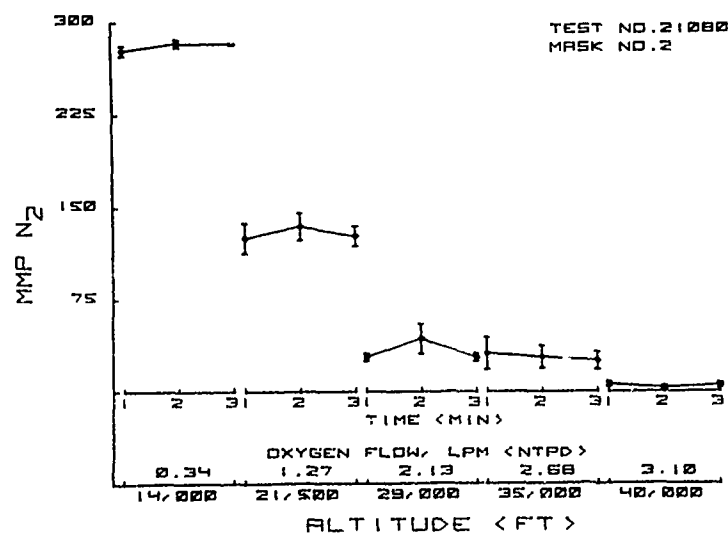


Figure 37. Partial pressure of end expiratory nitrogen in mmHg at each altitude and oxygen flow. Subject No. 210.

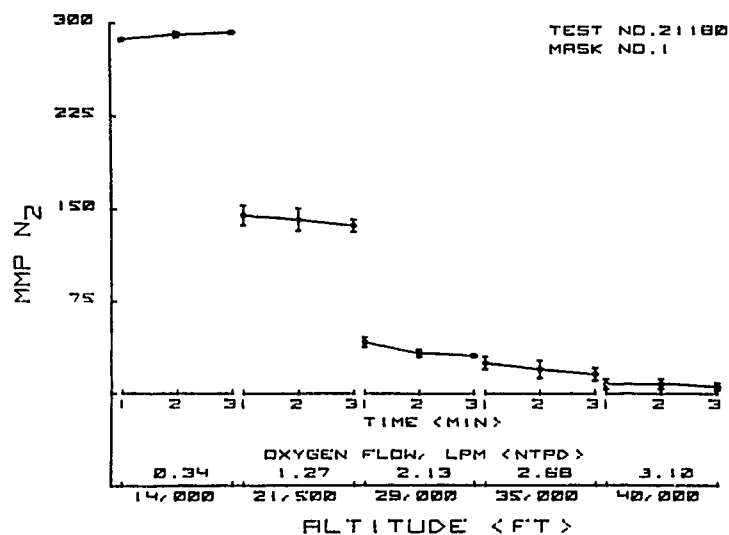


Figure 38. Partial pressure of end expiratory nitrogen in mmHg at each altitude and oxygen flow. Subject No. 211.

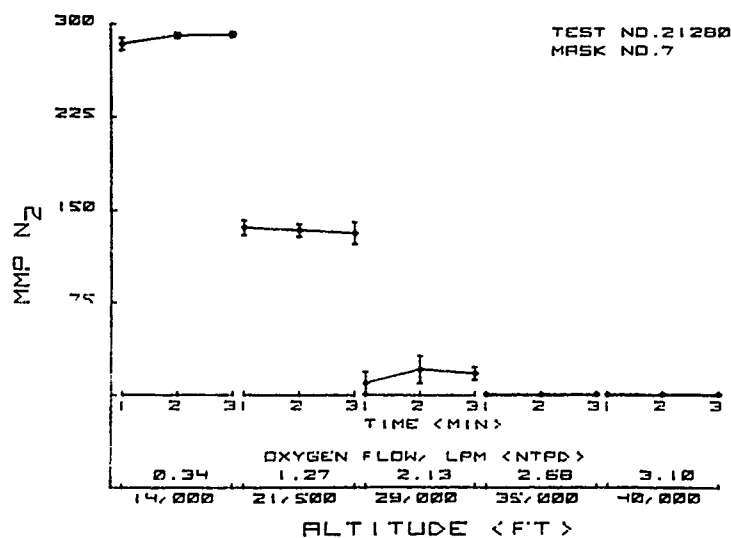


Figure 39. Partial pressure of end expiratory nitrogen in mmHg at each altitude and oxygen flow. Subject No. 212.

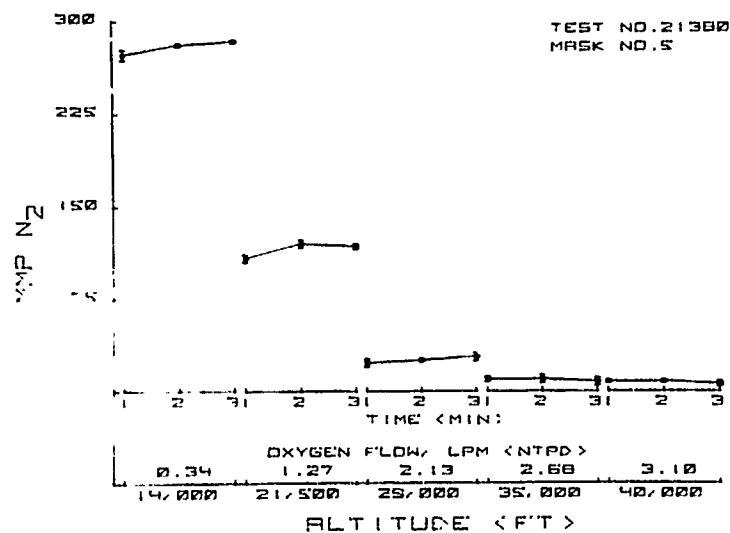


Figure 40. Partial pressure of end expiratory nitrogen in mmHg at each altitude and oxygen flow. Subject No. 213.

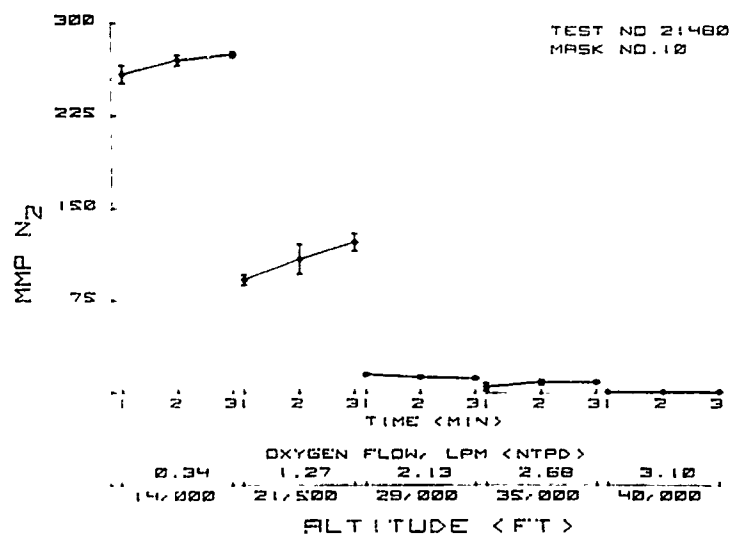


Figure 41. Partial pressure of end expiratory nitrogen in mmHg at each altitude and oxygen flow. Subject No. 214.

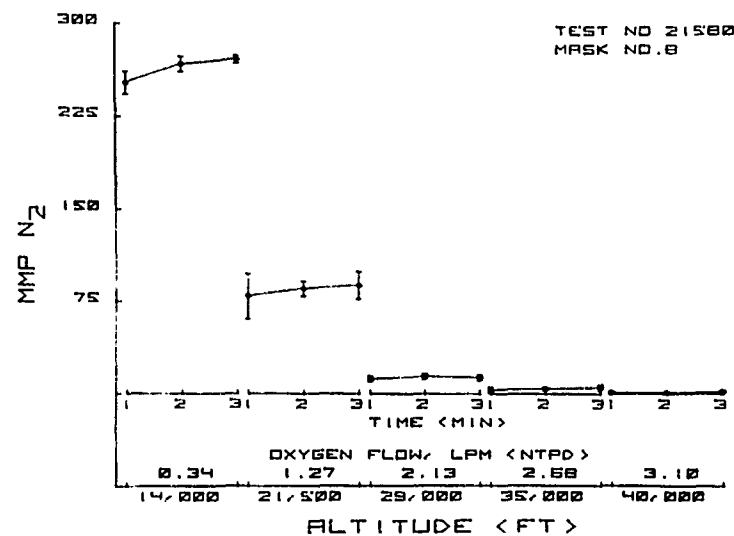


Figure 42. Partial pressure of end expiratory nitrogen in mmHg at each altitude and oxygen flow. Subject No. 215.

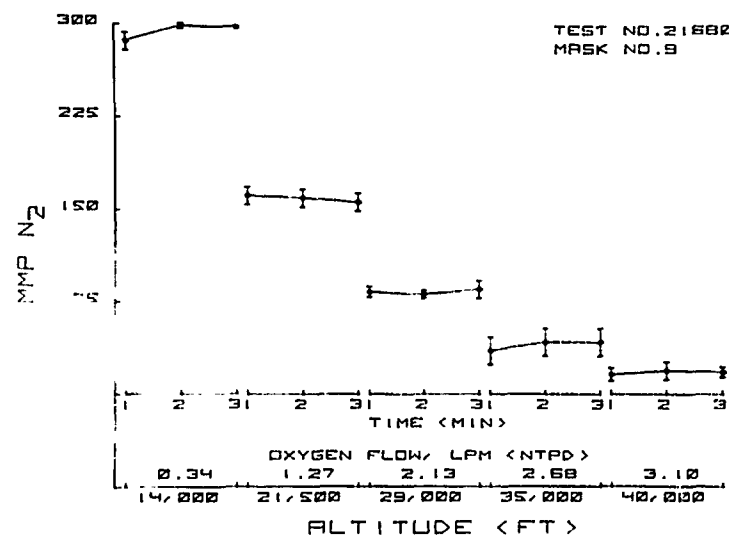


Figure 43. Partial pressure of end expiratory nitrogen in mmHg at each altitude and oxygen flow. Subject No. 216.

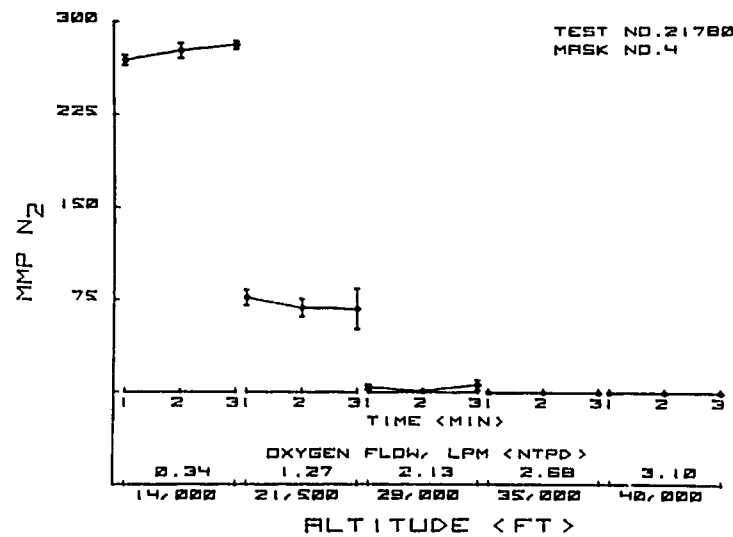


Figure 44. Partial pressure of end expiratory nitrogen in mmHg at each altitude and oxygen flow. Subject No. 217.

CONCLUSIONS

Using the gas analysis method specified in NAS-1179, the test mask did meet the performance requirements for end expiratory oxygen levels when tested in an altitude chamber to the equivalent of 40,000 ft. The oxygen flow curve to the mask was sufficient at all altitudes tested, with the 14,000-ft altitude having the most critical flow. The oxygen flow was sufficient to provide for approximately a 30-L/min-BTPS respiratory minute volume at 35,000 ft.

References

1. Federal Aviation Administration: Technical Standard Order C-64, April 1967.
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3. Anthropometry for Respirator Sizing. U.S. Department of Health, Education, and Welfare, April 1972.